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On the EDM Cancellations in D-brane models

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Abstract

We analyze the possibility of simultaneous electron, neutron, and mercury electric dipole moment (EDM) cancellations in the mSUGRA and D–brane models. We find that the mercury EDM constraint practically rules out the cancellation scenario in D-brane models whereas in the context of mSUGRA it is still allowed with some fine-tuning.

One of the most important tests of CP-violation comes from the measurements of the electric dipole moments (EDMs). Non-observation of the EDMs imposes severe constraints on models for physics beyond the Standard Model. The most stringent of these come from continued efforts to measure the EDMs of the neutron [1], electron [2], and mercury atom [3]

$$\begin{aligned} d_n &< 6.3 \times 10^{-26} \text{ e cm } (90\% CL), \\ d_e &< 4.3 \times 10^{-27} \text{ e cm }, \\ d_{Hg} &< 2.1 \times 10^{-28} \text{ e cm }. \end{aligned} \tag{1}$$

In particular, these constraints are a difficult hurdle for supersymmetric theories if they are to allow sufficient baryogenesis. Indeed it is remarkable that the SM contribution to the EDM of the neutron is of order 10^{-30} e cm, whereas the "generic" supersymmetric value is 10^{-22}e cm.

There are several proposals to reconcile the EDM constraints and supersymmetry. The EDM bounds may imply that the supersymmetric CP-phases are small [4] or the sfermions of the first two generations are heavy [5]. Alternatively, they may imply that CP violation has a flavor-off-diagonal character [6]. It has also been realized that in certain regions of the parameter space the constraints on the CP-phases are not severe due to the EDM cancellations [7]. This last possibility will be the subject of our present study. In particular, it has recently been found that simultaneous neutron and electron EDM cancellations may occur in certain D-brane-motivated models [8] (see also [9]). We critically examine theoretical aspects of the model of Ref.[8] and analyze whether this scenario satisfies all of the experimental EDM constraints.

In our analysis, we follow the approach of Ibrahim and Nath [7], and include contributions of the electromagnetic, chromomagnetic, and Weinberg operators to the neutron EDM via Naive Dimensional Analysis (a better justified approach to the NEDM based on the QCD sum rules has recently appeared in [10]). We have also included the Barr-Zee type contributions to the EDMs [11] and the gluino-bottom-sbottom contribution to the Weinberg operator. In addition to the electron and neutron EDM constraints, we impose the EDM constraint for the mercury atom. It has been realized that the mercury EDM is mostly sensitive to the quark chromomagnetic dipole moments and that the constraint $d_{Hg} < 2.1 \times 10^{-28}$ e cm can be translated into [12]

$$|d_d^C - d_u^C - 0.012 d_s^C|/g_s < 7 \times 10^{-27} cm \ , \tag{2}$$

where g_s is the $SU(3)_c$ coupling constant and d_i^C are defined in the standard way [7]. This constraint will be crucial in our analysis. Before we proceed, let us briefly review basic ideas of the D-brane models (see also Refs.[13] and [14]).

Recent studies of type I strings have shown that it is possible to construct a number of models with non–universal soft SUSY breaking terms which are phenomenologically interesting. Type I models can contain 9-branes, 5_i-branes, 7_i-branes, and 3-branes where the index $i = 1, 2, 3$ denotes the complex compact coordinate which is included in the 5-brane world volume or which is orthogonal to the 7-brane world volume. However, to preserve $N = 1$ supersymmetry in $D = 4$ not all of these branes can be present simultaneously and we can have (at most) either D9-branes with D5_i-branes or D3-branes with D7_i-branes.

Gauge symmetry groups are associated with stacks of branes located "on top of each other". A stack of N branes corresponds to the group $U(N)$. The matter fields are associated with open strings which start and end on the branes. These strings may be attached to either the same stack of branes or two different sets of branes which have overlapping world volumes. The ends of the string carry quantum numbers associated with the symmetry groups of the branes. For example, the quark fields have to be attached to the $U(3)$ set of branes, while the quark doublet fields also have to be attached to the $U(2)$ set of branes. Given a brane configuration, the Standard Model fields are constructed according to their quantum numbers.

The SM gauge group can be obtained in the context of D-brane scenarios from $U(3) \times U(2) \times U(1)$, where the $U(3)$ arises from three coincident branes, $U(2)$ arises from two coincident D-branes and $U(1)$ from one D-brane. As explained in detail in Ref.[14], there are different possibilities for embedding the SM gauge groups within these D-branes. It was shown that if the SM gauge groups come from the same set of D-branes, one cannot produce the correct values for the gauge couplings $\alpha_j(M_Z)$ and the presence of additional matter (doublets and triplets) is necessary to obtain the experimental values of the couplings [15]. On the other hand, the assumption that the SM gauge groups originate from different sets of D-branes leads in a natural way to intermediate values for the string scale $M_S \simeq 10^{10-12}$ GeV [14]. In this case, the analysis of the soft terms has been done under the assumption that only the dilaton and moduli fields contribute to supersymmetry breaking and it has been found that these soft terms are generically non–universal. The MSSM fields arising from open strings are shown in Fig.1. For example,

the up quark singlets u^c are states of the type C^{95_3}, the quark doublets are C^{95_1}, etc. The presence of extra (D_q) branes which are not associated with the SM gauge groups is often necessary to reproduce the correct hypercharge and to cancel non-vanishing tadpoles.

Recently there has been a considerable interest in supersymmetric models derived from D-branes [8],[9]. In the model of Ref.[8], the gauge group $SU(3)_c \times U(1)_Y$ was associated with 5_1 branes and $SU(2)_L$ was associated with 5_2 branes. It was shown that in this model the gaugino masses are non–universal ($M_1 = M_3 \neq M_2$) so that the physical CP phases are $\phi_1 = \phi_3$, ϕ_A and ϕ_μ. It was emphasized that the non–universal gaugino phases have an important impact on enlarging the regions of the parameter space where the EDM cancellations occur.

However, closer inspection reveals that such a model cannot produce the correct hypercharge assignment for all of the SM fields. In fact, this model does not distinguish between the up and down quarks, H_1 and H_2, etc. which have different hypercharges and thus cannot be realistic. In realistic models, the hypercharge $U(1)$ is an anomaly-free linear combination of two or three $U(1)$'s arising from different sets of branes. As a result, the relation $\phi_1 = \phi_3$ can only be obtained if one embeds the SM gauge group within the same set of branes. However, in this case the gaugino masses are universal and the gaugino phase can be rotated away. The relation $\phi_1 = \phi_3 \neq \phi_2$, which was found to be important for the EDM cancellations, does not appear to hold in realistic models. Therefore in what follows, we will consider the EDM cancellations in both the model of Ref.[8] and a more realistic model. We shall find that in both cases, although simultaneous EEDM and NEDM cancellations can occur in considerable regions of the parameter space, imposing the mercury constraint practically rules out the cancellation scenario.

Let us begin by constructing a more realistic D-brane scenario. In order to obtain a model which is close in spirit to that of Ref.[8], one may place the $U(1)$ brane on top of the $U(3)$ branes. This however implies that the string scale M_S is 6×10^8 GeV which leads to $m_{3/2} \approx M_S^2/M_{Pl} \sim 10^{-1}$ GeV [14], too low a value for the SUSY particle masses. Extra light matter fields are required to mitigate this problem. Another possibility is to consider a model without the $U(1)$ brane. This option is also problematic since in this case the up-type Yukawa couplings are not allowed [14] resulting in a negligible top quark mass, whereas the lepton Yukawa couplings are allowed. It is difficult to imagine how this scenario can account for the observed fermion masses. Therefore, both of these simplified versions of the model are hardly phenomenologically viable.

The model in which $U(3)$, $U(2)$, and $U(1)$ originate from different sets of branes is much more phenomenologically attractive. In this case one naturally obtains an intermediate string scale ($10^{10} - 10^{12}$ GeV), although higher values up to 10^{16} GeV are still allowed. The Yukawa couplings are also more realistic: both the up and the down type Yukawa interactions are allowed, while that for the leptons typically vanishes (depending on further details of the model) [14]. The hypercharge is expressed in terms of the $U(1)$ charges $Q_{1,2,3}$ of the $U(1)_{1,2,3}$ groups:

$$Y = -\frac{1}{3}Q_3 - \frac{1}{2}Q_2 + Q_1 \ , \tag{3}$$

with the following (Q_3, Q_2, Q_1) charge assignment:

$$q = (1,-1,0) \ , \ u^c = (-1,0,-1) \ , \ d^c = (-1,0,0) \ , \tag{4}$$

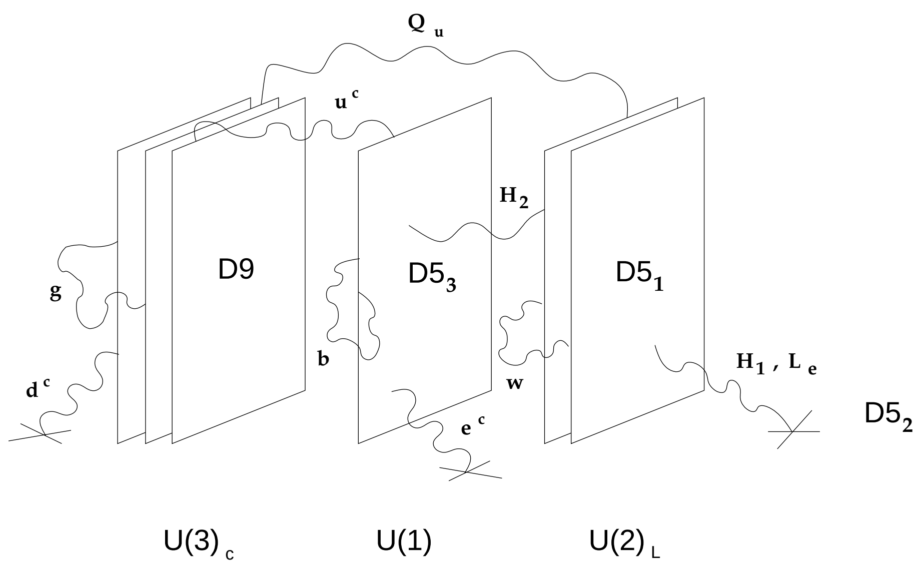

Figure 1: Embedding the SM gauge group within different sets of D-branes. The extra D_q brane (5_2) is marked by a cross.

$$
\begin{aligned}
& l=(0,1,0)\ ,\ e^c=(0,0,1)\ , \\
& H_2=(0,1,1)\ ,\ H_1=(0,1,0)\ .
\end{aligned}
$$

Using the standard parameterization [13]:

$$
\begin{aligned}
F^S &= \sqrt{3}(S+S^*)m_{3/2}\sin\theta\ e^{-i\alpha_s}\ , \\
F^i &= \sqrt{3}(T_i+T_i^*)m_{3/2}\cos\theta\ \Theta_i e^{-i\alpha_i}\ ,
\end{aligned} \tag{5}
$$

and setting $\Theta_3=0$ for simplicity, the gaugino masses in this model can be written as

$$
\begin{aligned}
M_3 &= \sqrt{3}m_{3/2}\sin\theta\ e^{-i\alpha_s}\ , \qquad (6) \\
M_2 &= \sqrt{3}m_{3/2}\ \Theta_1\cos\theta\ e^{-i\alpha_1}\ , \\
M_Y &= \sqrt{3}m_{3/2}\ \alpha_Y(M_S)\left(\frac{1}{\alpha_2(M_S)}\Theta_1\cos\theta e^{-i\alpha_1}+\frac{2}{3\alpha_3(M_S)}\sin\theta e^{-i\alpha_s}\right)\ ,
\end{aligned}
$$

where

$$
\frac{1}{\alpha_Y(M_S)}=\frac{2}{\alpha_1(M_S)}+\frac{1}{\alpha_2(M_S)}+\frac{2}{3\alpha_3(M_S)}\ . \tag{7}
$$

Here α_k correspond to the gauge couplings of the $U(k)$ branes. As shown in Ref.[14], $\alpha_1(M_S)\simeq 0.1$ leads to the string scale $M_S\approx 10^{12}$ GeV. Note that $\phi_3=\phi_Y$ if $\Theta_1=0$; this is however phenomenologically unacceptable since in this case $M_2=0$ and the chargino is too light. The soft scalar masses are given by

$$
m_q^2 = m_{3/2}^2\left[1-\frac{3}{2}\left(1-\Theta_1^2\right)\cos^2\theta\right]\ ,
$$

$$
\begin{aligned}
m_{d^c}^2 &= m_{3/2}^2\left[1-\frac{3}{2}\left(1-\Theta_2^2\right)\cos^2\theta\right] , \\
m_{u^c}^2 &= m_{3/2}^2\left[1-\frac{3}{2}\cos^2\theta\right] , \\
m_{e^c}^2 &= m_{3/2}^2\left[1-\frac{3}{2}\left(\sin^2\theta+\Theta_1^2\cos^2\theta\right)\right] , \\
m_l^2 &= m_{3/2}^2\left[1-\frac{3}{2}\sin^2\theta\right] , \\
m_{H_2}^2 &= m_{3/2}^2\left[1-\frac{3}{2}\left(\sin^2\theta+\Theta_2^2\cos^2\theta\right)\right] , \\
m_{H_1}^2 &= m_l^2 , \qquad (8)
\end{aligned}
$$

and the trilinear parameters are

$$
A_u = \frac{\sqrt{3}}{2}m_{3/2}\left[\left(\Theta_2 e^{-i\alpha_2}-\Theta_1 e^{-i\alpha_1}\right)\cos\theta-\sin\theta\; e^{-i\alpha_s}\right] , \qquad (9)
$$

$$
A_d = \frac{\sqrt{3}}{2}m_{3/2}\left[-\left(\Theta_1 e^{-i\alpha_1}+\Theta_2 e^{-i\alpha_2}\right)\cos\theta-\sin\theta\; e^{-i\alpha_s}\right] , \qquad (10)
$$

$$
A_e = 0. \qquad (11)
$$

We note that the Yukawa couplings in Type I models are either 0 or 1, so an additional mechanism is needed to produce the observed femion masses and mixings.

In our EDM analysis, we rotate away the phase of M_2 by a $U(1)_R$ transformation (the phase of $B\mu$ can also be set to zero by a $U(1)_{PQ}$ rotation). We observe that the angles Θ_i and θ are quite constrained if we are to avoid negative mass-squared's for squarks and sleptons. For definiteness we assume $\alpha_1 = \alpha_2$. Then the soft terms are parameterized in terms of the phase $\phi \equiv \alpha_1 - \alpha_s$.

In Fig.2 we display the bands allowed by the electron (red), neutron (green), and mercury (blue) EDMs. In this figure, we set $m_{3/2} = 150$ GeV, $\tan\beta = 3$, $\Theta_1^2 = \Theta_2^2 = 1/2$, $\cos^2\theta = 2\sin^2\theta = 2/3$, and $\alpha_1(M_S) \sim 1$ with M_S being the GUT scale. For the plot to be more illustrative, we do not impose any additional constraints besides the EDM ones (i.e. bounds on the chargino and slepton masses, etc.). It is clear that even though simultaneous EEDM/NEDM cancellations allow the phase ϕ to be $\mathcal{O}(1)$, an addition of the mercury constraint requires all phases to be very small (modulo π) and thus practically rules out the cancellation scenario in this context. We find that the mercury EDM behaviour in D-brane models is very different from that of the electron and neutron and thus is crucial in constraining the parameter space.

Next we consider the model of Ref.[8]. As we have argued above, this model can hardly be obtained from D-branes, however one may treat it as an interesting phenomenological scenario motivated by D-branes. The (corrected) soft terms for this model read (for $\Theta_3 = 0$)

$$
\begin{aligned}
&M_Y = M_3 = -A = \sqrt{3}m_{3/2}\cos\theta\;\Theta_1 e^{-i\alpha_1} , \\
&M_2 = \sqrt{3}m_{3/2}\cos\theta\;\Theta_2 e^{-i\alpha_2} , \\
&m_L^2 = m_{3/2}^2(1-\frac{3}{2}\sin^2\theta);
\end{aligned}
$$

$$m_R^2 = m_{3/2}^2(1 - 3\cos^2\theta\ \Theta_2^2)\ . \qquad (12)$$

To illustrate the EDM constraints, we choose the parameters which allow for simultaneous EEDM/NEDM cancellations, namely $m_{3/2} = 150$ GeV, $\tan\beta = 2$, $\Theta_1 = 0.9$, and $\theta = 0.4$ as given in Ref.[8]. Fig.3 shows that the mercury constraint has the same behaviour as in the model considered above and rules out large CP-phases.

Finally, we examine the possibility of simultaneous EDM cancellations in mSUGRA. In contrast to the D-brane models, all of the EDM constraints have similar behaviour in the (ϕ_A, ϕ_μ) plane. In fact they can be approximately described by the relation $\phi_\mu \simeq -a \sin\phi_A$ with $a > 0$. With a favorable choice of the parameters, the three bands will have a significant overlap. In Fig.4 we present points allowed by all three EDM constraints with all the masses set to 200 GeV, $\tan\beta = 3$, and $A = 40$ GeV. Although ϕ_A is unconstrained in this case, the phase ϕ_μ is required to be $\mathcal{O}(10^{-2})$. To relax this bound one has to either increase the mass scale of the susy spectrum or restrict the range of ϕ_A. Our mSUGRA results are in agreement with those of Refs.[12] and [16].

These results reveal that, putting aside the fine-tuning issues, the EDM cancellation scenario is much more favored in the mSUGRA framework than in the D-brane models. This qualitatively agrees with the analysis of Ref.[16] where it was found that in mSUGRA one out of every 10^2 points in the parameter space satisfies the EDM constraints, while for the non-universal case this fraction drastically reduces to $1/10^5$.

To conclude, we have analyzed a possibility of simultaneous electron, neutron, and mercury EDM cancellations in D-brane models and mSUGRA. We find that such cancellations cannot occur in presently available semi-realistic D-brane models, while in the mSUGRA framework these cancellations are allowed with some fine-tuning.

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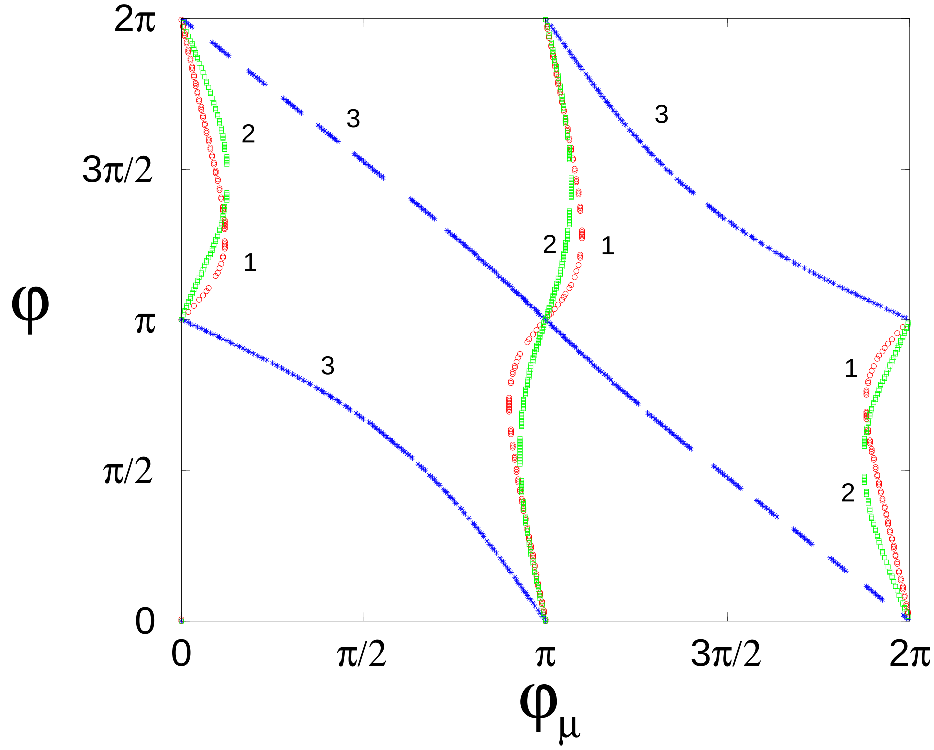

Figure 2: Bands allowed by the electron (1), neutron (2), and mercury (3) EDMs in the D-brane model. The corresponding SUSY parameters are given in the text.

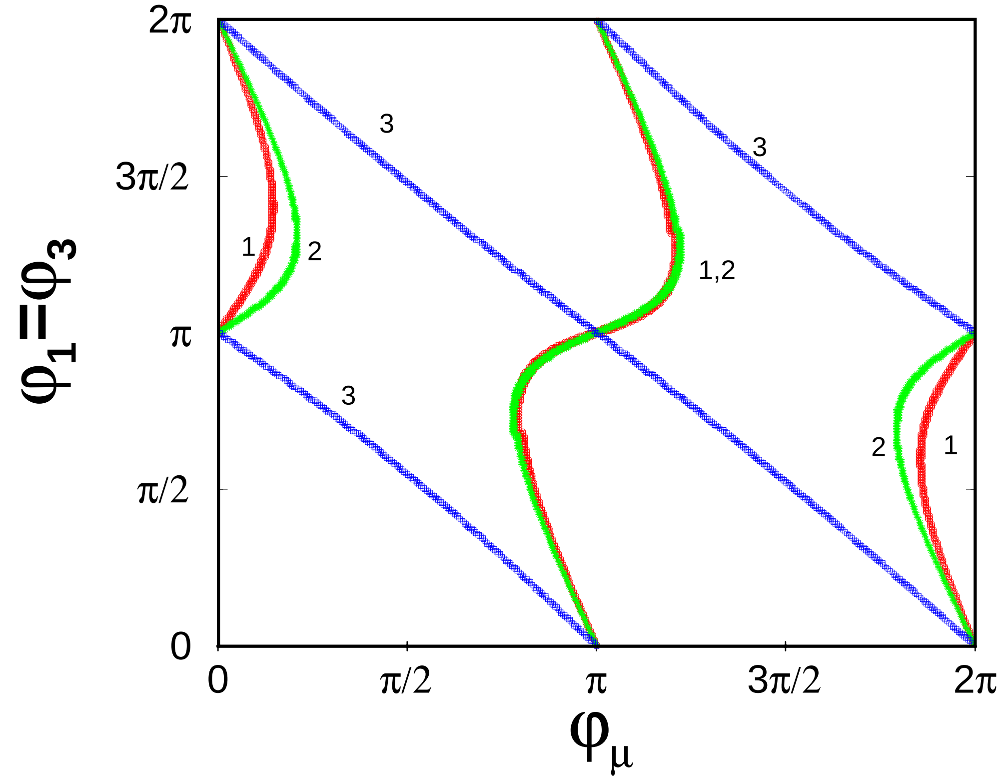

Figure 3: Bands allowed by the electron (1), neutron (2), and mercury (3) EDMs for the model of Ref.[8]. The corresponding SUSY parameters are given in the text.

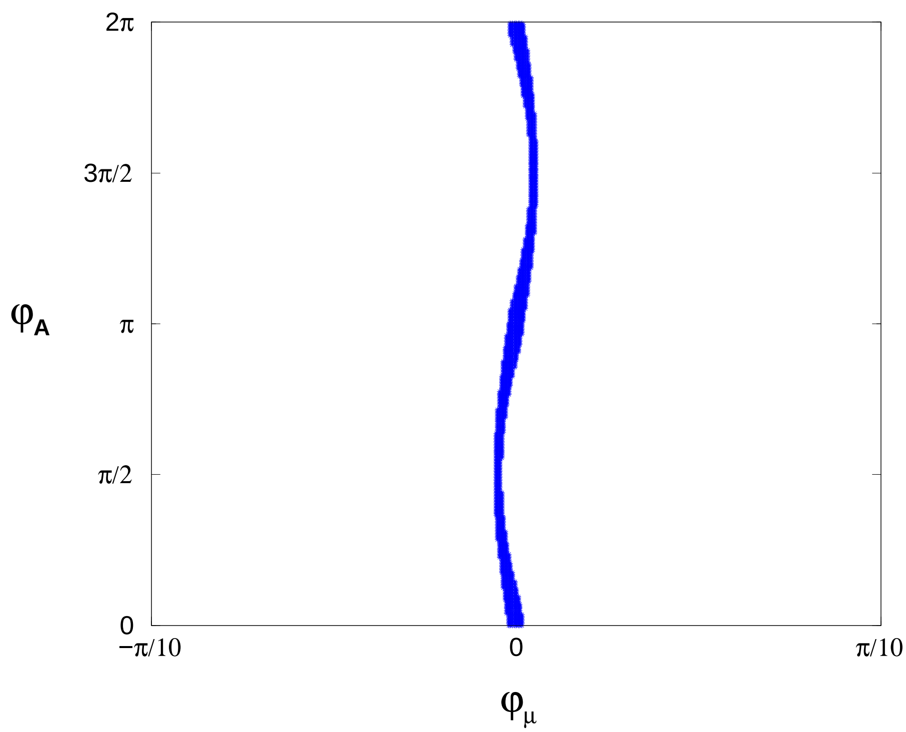

Figure 4: Points allowed by simultaneous electron, neutron, and mercury EDM cancellations in mSUGRA. The corresponding SUSY parameters are given in the text.